Denny Way/Lake Union CSO Project
Contract A

Technical Memorandum - T3

Tunnel Cleaning

Prepared for
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Prepared by
Black & Veatch

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1.0 Introduction

The proposed Mercer Street Tunnel will store combined sewer flows that would otherwise be released to Elliott Bay during major storm events. As that flow is stored in the tunnel, suspended solids and sediment will settle to the tunnel floor. This technical memorandum predicts the amount of sediment that will settle, and provides an evaluation of alternative methods of removing it from the tunnel. Several options are investigated but the focus is on flushing of the tunnel to prevent settled sediment from building up and causing immediate odor and long-term volume-reduction problems.

2.0 Deposition and Sediment Characteristics

This section describes the physical attributes of suspended sediment and the tunnel layout as well as the physical process of sediment transport (scour).

2.1 Monitoring Report

The quantity and characteristics of the suspended solids are described in the June *1997 Monitoring Report,* prepared by Brown & Caldwell/Herrera Environmental Consultants. Items of interest in that report include Table *5* and Figure 5. Since the potential for long residence times in the tunnel exists, the Total Suspended Solids (TSS) information shown on Table 5 was used to determine potential solids loading. This number is greater than the Settlable Solids (SS), and for the purposes of tunnel cleaning will provide a more conservative design goal.

The mean TSS concentrations noted in Table *5* of the monitoring report varied from 63.2 to 120.5 mg/l. To provide for a more conservative flushing design the incoming load was taken as 120 mg/l.

2.2 Estimated Solids Loading

Table 1 lists the estimated solids loading in pounds per year for various solids removal efficiencies and annual CSO volumes. The average annual inflow into the tunnel is estimated to be 611 million gallons. The "worst case" solids loading condition based .on 611 million gallons per year and 120 mg/I TSS concentration is 612,200 pounds per year, or 1,002 lb./MG of CSO volume.

Table 1
Estimated Annual Solids Removal (Pounds per Year)
Based on Influent TSS concentration of *120* mg/I

Annual CSO Volume (MG)	Influent TSS Load (lbs/year)	50% TSS Removal	75% TSS Removal	100% TSS Removal
100	100,200	50,100	75,150	100,200
200	200,400	100,200	150,300	200,400
300	300,600	150,300	225,450	300,600
400	400,800	200,400	300,600	400,800
500	501,000	250,500	375,750	501,000
611	612,200	306,100	459,170	612,200

.Solids deposition, depending on the solids density, of between 2 to *3* inches could be experienced within the tunnel per year. Note that if solids are allowed to accumulate, lower layers would tend to consolidate and increase in density. This would reduce the apparent build-up rate, but would increase the work required to dislodge the solids.

If the tunnel is not cleaned by some method on an ongoing basis, solids are expected to accumulate until the tunnel section is reduced sufficiently to increase flow velocity through the tunnel. Odor from the solids and sediment would be an ongoing problem. Loss of usable volume would become a problem over the course of many years. Since neither of these problems is an acceptable situation, ongoing cleaning is desirable.

The *Monitoring Report* determined that the mean settling velocity for the sediment is 0.017 cm/sec. This is considerably less than for sand, for which most sediment transport equations are written. During severe storms, there will be some carry-through of the lighter fractions of the solids. However, in many other cases the relatively long detention time in the tunnel will result in the tunnel solids removal exceeding a typical primary settling tank solids removal.

2.3 Scouring

Scouring is actually a form of solids or sediment transport. Solids are transported either by being rolled along the bottom of a channel or by being suspended in the fluid. Suspension in the fluid is a far more efficient means of transporting solids but, depending on the size and weight of the particles, can require higher flow velocities.

Rolling the sediment along the bottom requires that sufficient tractive force be applied to the particle to initiate motion. Assuming uniform flow, the tractive force is proportional to the component of the fluid weight parallel to the channel slope divided by the area of the channel. When other factors are held constant deeper flow and increased slope result in increased force applied on the particles. An increased velocity is implied by an increase in either of these two factors with other factors held constant.

Suspending a particle requires that the particle-settling velocity be exceeded in turbulent flow with upwellings. This velocity is higher than would be required to roll a particle along the bottom. The goal for efficient transport is to exceed the settling velocity of the particles to be moved.

There is a great deal of study in the area of sediment transport and a number of methods have been developed for determining sediment transfer rate. Some of the equations are based on sand flume research and some also consider actually-measured rates for rivers. In either case, the type of particles ' available for movement influences the development of the equations. The particles are generally assumed to be rock (higher specific gravity and more difficult to move). Use of these equations would tend to yield a more conservative design, as a significant fraction (around half) of the suspended solids (based on sampling for this project) are volatile and likely to have a specific gravity lower than rock (or larger diameter for a given particle weight). The minimum desirable velocity is between 2 and 3 feet per second (preferably closer to 3 feet per second to move grit).,

3.0 Tunnel Vertical Profile

'Me tunnel slope and cross section impact the ability to clean the tunnel using open channel flows alone. The sediment transport ability of the tunnel relates directly to its hydraulic characteristics. The characteristics of the sediment in turn define the likely buildup and flushing rates.

The May 1997 Facilities Plan proposed a tunnel configuration (6,100 feet in length with 5 feet elevation difference) consisting of the following components:

- East Portal/Drop Structure.
- 5,800 feet of 14.5-foot-inside-diameter tunnel.
- West Portal.
- 300 feet of 12-foot-diameter pipe crossing under Elliott Avenue West.

Another tunnel vertical profile alternative was also evaluated to determine the sensitivity of cleaning potential to slope changes. The alternative tunnel vertical profile configuration (6,100 feet in length with 10 feet elevation difference) consists of the following components:

- East Portal/Drop Structure.
- 6,100 feet of 14.5-foot-inside-diameter tunnel.

3.1 Tunnel Slope

The 30% Design has adopted the alternative with a slope of.000129 ft/ft. A steeper slope will increase flow velocities and make the tunnel easier to clean with less water. Table 2 shows the effects of a steeper slope given a flow of 24 MGD (3 feet per second for the shallower slope alternative) through the tunnel.

Table 2
Tunnel Slope, Flow Velocity and Sediment Transport Capacity

Slope (ft/ft)	Velocity (fps)	Relative Sediment Transport Capacity
0.0008	3.1	1.0
0.00164	3.7	1.7

The steeper the tunnel, the less effort is assumed to be needed to clean the tunnel and the lower the annual maintenance costs. Assumptions utilized in this analysis included: average sediment transport per Colby and Bangold (equations discussed below) and amount of flushing water will be increased at flatter slopes to match the effect at steeper slopes. More flushing iterations will be required at flatter slopes.

A steeper tunnel will also result in more of the sediment being carried farther down the tunnel as the tunnel fills. However, the backwater would not extend up to the upstream end of a steeper tunnel until the tunnel was filled to a greater degree as compared with a tunnel with a lower slope. Once the tunnel is filled to the point where the backwater extends for the length of the tunnel, no further cleaning benefit will occur from additional flow.

3.2 Tunnel Section

The tunnel section could include a low flow channel (cunette). Such a cunette can be formed by casting shelves on either side of the circular tunnel section. This channel will increase the available velocity and energy to carry sediment at low flows. That, combined with shelves sloping towards the cunette, will improve the utility of lower flows for sediment removal. The minimum cunette size that would support a flow of 2 to 3 fps was determined (using 6 inch increments in size for the half pipes). Table 3 lists the cunette sizes for the two tunnel vertical profile alternatives.

Table 3
Tunnel Cunette Width and Velocities at 24 mgd

Slope (ft/ft)	Cunette Width (in)	Cunette Depth (in)	Velocity (fps)	Flow (cfs)
0.0008	36	18	2.3	8.4
0.00164	18	18	3.0	6.6

As can be seen in the above table, it is difficult to get a cunette that will attain sufficient velocity even at relatively high flow rates for the lower slope option. The steeper option allows a smaller cunette with less flow while maintaining a higher velocity.

For the purposes of modeling the full tunnel, the Facilities Plan tunnel configuration assumed a 36-inch-wide, half-pipe cunette, and the alternative tunnel configuration assumed a cunette about 18 inches square. The shelf was assumed to be flat on either side of the cunette.

The Facilities Plan stated that if a centerline cunette is placed by infilling a circular section, the shelves adjacent to the cunette may accumulate sediment due to their low slope. King County maintenance staff indicated that as flow exceeds the capacity of the cunette, it will tend to scour the immediately adjacent shelf area. However, as flow extends farther out along the shelf, sediment would likely remain. This accumulation at the sides is also enhanced by the sediment accumulation sliding down the side wall to the shelves.

Multiple cunettes could be utilized to reduce the amount of shelf area, but these would reduce accessibility within the tunnel except with specialized equipment. The cunettes would act as a rutted road and large tires with the correct spacing would be required for travel using the cunettes as wheel guides. A single cunette could be straddled but would require careful driving, depending on cunette and vehicle width.

If a cunette were not installed, a significant flushing flow that covered a large portion of the tunnel cross section with a significant depth would be required to achieve any practical sediment transport. For this reason, a cunette would be useful whenever the tunnel was subjected to a cleaning process. During low flow conditions, the cunette would carry sediment and debris loosened by localized washing that would otherwise remain to be moved throughout the entire tunnel length.

3.3 Tunnel Linings

The use of a smooth lining material Such as PVC or another plastic to aid in tunnel cleaning was also evaluated. This option would provide a low friction surface which would reduce the force required to initiate motion of deposited particles (see section 3.4, Scouring, below).

The disadvantages of a plastic lining are that the plastic lining would only enhance the fluid velocity after it was exposed (after scouring has been completed). It would only serve as a low friction surface to initiate sediment bed motion where the shear force was transmitted completely through the sediment bed to the sediment/lining interface. Flow energy tends to be transferred into movement of the top layers of particles in a bed rather than bulk movement of the bed.

Such a lining would also be subjected to damage from large particles, high velocities, delamination, and when people and equipment enter the tunnel. Walking on such a surface could also be hazardous until it was sufficiently scarred to provide traction. It is recommended that plastic lining not be installed because of potential maintenance problems and limited effectiveness in aiding sediment transport.

3.4 Scouring Velocities

To determine the minimum scouring velocities for sediment transport for both tunnel alternatives, a spreadsheet was developed to look at possible tunnel sections, the flow characteristics at increments of depth of 0.10 ft and the amount of sediment carried at those depths. Three transport equations from Colby, Bagnold and Yang, as presented in Simons and Senturk (2) were used.

The answers provided by the equations diverged greatly (as is common with sediment transport equations). However, some general trends were noted in the Colby and Bagnold equations.

Flow in the steeper tunnel option is faster so sediment transport is more efficient, as discussed above. Providing more slope will greatly reduce the amount of flushing required and reduce tunnel cleaning costs.

Transport is likely to be most effective at a depth that fully covers the shelves adjacent to the cunette with flow at an acceptable velocity. Transport is less effective if flow extends toward the top of the tunnel because the velocity will be decreased in accordance with circular pipe section properties.

The minimum desirable velocity is between 2 and 3 feet per second (preferably closer to 3 feet per second to move grit). The depths and flows associated with a velocity of 3 fps are shown in Table 4:

Table 4
Depth and Flow for 3 fps Cleaning Velocity at Alternative Slopes

Slope (ft/ft)	Depth o flow (ft)	Flow (mgd)	Cunette Flow Condition
0.00164	1.5	4.2	Cunette full
0.00164	2.1	15.5	Flow across tunnel width
0.0008	1.5	6.0	Cunette full (velocity is only 2.67 fps)
0.0008	2.4	24.0	Flow across tunnel width

The steeper tunnel option will achieve cleaning velocities while u'sinc, considerably less water. For the flatter option, if more water in the form of iterative flushing is required, there will be an ongoing cost associated with the increased amount of water used for flushing.

There is a publication available from the EPA (1, Pisano) that covers deposition and flushing, specifically in smaller conveyance pipes. The author has continued his research and later papers are available. However, this publication summarizes and references a number of other papers. Two publications are referenced (1.28, Sonnen and 1.30, Yao) that cover sediment transport. Specifically, Yao provides design shear stresses for self-cleaning. These are 0.02 to 0.04 psf for particles 0.2 to 1.0 mm in size with a shear stress of 0.06 to 0.08 psf for larger particles. Pisano appears to equate the ability to carry a given sediment particle with its settling velocity in this publication.

The calculations for this factor are summarized in Table 5 which indicates the depth and flow rate at which the shear stress reached 0.06 psf.

Table 5
Depth and Flow for Shear Stress of 0.06 PSF

Slope (ft/ft)	Depth of flow (ft)	Flow (mgd)	Cunette Flow Condition (assuming cunette is in place)
0.00164	2.2	18.9	Flow across tunnel width
0.0008	2.9	42.5	Flow across tunnel width

The ability of the steep tunnel option for better cleaning is evident. The steeper option can achieve the desirable shear force with less flow. The shallower slope needs higher flows to meet the criteria.

In general the values that were used in selection of minimum acceptable flows were (in order of priority and relative certainty): velocity, shear stress, and most effective sediment transport.

While all flow enters the tunnel over weirs, it is possible for floatable material to enter, settle out, and become immovable. For instance, a bottle could float in and then fill with fluid, becoming a much more difficult item to move. The goal would not be to move large objects but rather to scour around them as much as possible. Some increase in deposition would be expected around a large obstruction but the goal would be to limit the area where deposition occurred. Hopefully, the incidence of large items is limited so that periods between cleaning are extended.

4.0 Cleaning Methods

This section will evaluate alternative cleaning methods. Methods that are rejected as not feasible are also discussed. There are a variety of possible methods for cleaning the tunnel. There are also physical limitations and maintenance constraints that are assumed in evaluating the alternative tunnel-cleaning methods. The primary constraint is the assumption that the tunnel will not be entered by maintenance and inspection staff on a regular basis. This restriction severely limits routine cleaning options that require entry into the tunnel for manual cleaning or maintenance of mechanical or piped systems.

Capital and annual or per-cleaning costs have been estimated. These are planning-level cost estimates for use in comparing alternatives. Further refinement will be necessary to develop final designs and design-level cost estimates.

4.1 Manual Methods

Manual cleaning would be performed on a periodic basis. Typically, periodic cleaning is performed at 5- to 25-year intervals. The County typically has contracted such cleaning jobs. Entry, ventilation, and working constraints must be included in any manual-cleaning contract requirements.

The estimated cost for manual cleaning is approximately $101,000/cleaning, based on the following assumptions:

- Time required will be one week.
- Total crew size will be 9 persons (3 in tunnel, 6 on surface).
- Capital cost of access point for "Bobcat"-sized piece of is equipment included.
- Equipment costs include fans (2 @ 5,000 cfm), communication equipment, backflow-prevention and air-monitoring equipment.
- Material costs assume 1,500 gpm from adjacent potable sources during cleaning.

4.2 Mechanical Methods

The "no entry" constraint eliminated mechanical methods such as rakes or mixers from further consideration. These could break down by jamming, corrosion or other mechanical failure and Would require tunnel entry to repair.

Other mechanical methods could be designed to meet the above constraints. However, the initial, operating and maintenance costs would vary. The methods are presented beginning with the least-favored methods, with the more-favorable methods following.

1. Air jets could be used to maintain particles in suspension or resuspend settled solids, with attendant costs for piping, compressors or blowers, the energy to run these, and maintenance of the system. The estimated cost for this system is approximately $2.1 million capital and $26,000 annually, based on the following assumptions:

- System will be designed to provide 0.75 horsepower per 1,000 cf when the tunnel is half full.
- Five compressor stations of 600 horsepower each will need to be sited.
- Power cost estimates are based on operation of the system for 4 hours, 10 times per year.

2. Water jets in the form of small spray nozzles or larger "monitor" nozzles could be used for localized cleaning. The area cleaned would be limited to the reach of individual nozzle streams as it is the stream velocity, not bulk flow, which would provide the motive velocity. A combination of nozzles directing sediment to a cunette could provide both short- and long-distance transport. This combination would also be capable of cleaning both the low slope shelves next to the cunette and transporting material along the cunette. There would be costs from the piping and maintenance of the piping. The source of water for these nozzles would have to be relatively clean to prevent clogging in the nozzles or other elements of the piping system. The estimated cost for this system is approximately $ 1.1 million capital. and $7,500 annually based on the following assumptions:
    - Potable water is assumed for flushing.
    - 16 backflow-preventer stations are required.
    - 8 nozzles are provided every ten feet.
    - Total water to clean system is used over an 8-hour period.
    - Cleaning will be done four times per year.

Possible sources of water for a nozzle system are limited to potable water, screened CSO water, and groundwater., These and other sources are discussed in section 5.0 . Sufficient flow quantity and hydraulic head would be required to move accumulated sediment. Pumping would be required for the screened CSO water and groundwater. Potable water would be available from pressurized water mains. The addition of pumping to the cost of the alternative would make it comparable to the use of air. Any system involving use of a piping system in the tunnel would probably require periodic maintenance.

4.3 Hydraulic Cleaning Methods

The remaining methods use the CSO flows as a means of cleaning the tunnel. The two methods include pulsed flow and steady flow. -Both of these forms of cleaning are limited by the pumping capacity available to drain the tunnel. The available capacity is limited by what could probably be accepted by the Elliott Bay Interceptor and the Interbay Pumping Station during dry weather flow. This is estimated at 60 mgd. However, a pulsed wave may exceed the available pumping capacity for short periods, assuming that the sediment-laden flow could be ponded in the lowest portion of the tunnel and could be resuspended as necessary with a later flush.

4.3.1 Steady Flow

Insertion of a steady flow into the tunnel would be constrained by the pumping capacity at the end of the tunnel and also by the flow capacity of the source of the water. It is not likely that sufficient water could be directed into the tunnel on a sustained basis to fully flush it and to provide enough depth to clean the width of the tunnel. Low flow rates also lack the efficient high specific energy that a high flow rate applies to transporting sediment.

4.3.2 Pulsed Flow Using "Dam-Break" Wave Action

Use of a stored wave of water would provide benefits over a steady flow of water through the tunnel. The water could be stored at low inflow rates compatible with the selected source. The water could then be released in quantities and flow rates that would optimize the scouring effect of the water. Pisano has indicated, consistent with the sediment transport equations, that the more the flow and the higher the flow rate, the better the scouring (limited by lowered velocities as flow approaches the full flow -capacity). However, flows far below the full flow or even the pump station rate were shown to meet the criteria of 3 fps and 0.06 psf noted above.

Flushing using "dam-break" waves is a method for which one company has developed a patented gate mechanism to be installed at the upstream end of the pipe being flushed. The mechanism would not require remotely-controlled operators for the release gate, but would require dedicated storage. That dedicated storage at the end of the tunnel and within the tunnel if a series of tanks were required would be a significant cost factor. The tanks proposed by the manufacturer would hold around 11,700 cf of water. 'Me layout the manufacturer proposes is nine tanks spaced at intervals within the tunnel.

The estimated cost for the "dam-break" system is approximately $950,000 capital cost and $15,000 annually based on the following assumptions:

- Potable water is used for flushing.
- Cleaning is done 8 times per year since water quantities are so low.
- External tankage is placed in ROW so that land costs will be low.

This type of system poses possible tunnel-access problems. The manufacturer's system would require access and it is not known if this could be mitigated by using external reservoirs. Piping from the reservoirs to the tunnel would still be required at multiple points within the tunnel. The estimated cost for the "dam-break" system using external reservoirs is the same as for the internal tankage.

4.3.3 Pulsed Flow Using Upstream CSO Pipeline Storage

Another alternative is to add gates at the East Portal/Drop Structure to allow storage of Water in the 72-inch Central Trunk CSO pipeline, the 72-inch diameter Lake Union Tunnel CSO pipeline, and the 72-inch diameter South Lake Union CSO pipeline upstream of the tunnel in the Lake Union area. There are 323,000 gallons or 43,181 cubic feet of storage available in the three pipelines (assuming the pipes can store to their upstream invert).

This storage would require the installation of control gates at the East Portal/Drop Structure. These added gates could be manipulated to release water at an optimal rate for flushing the tunnel. Control of these gates and collection of water at the end of storms will require additional level indication and controls. Water sources could include CSO water, low flows backed up from the Central Trunk and Lake Union Tunnel or potable water.

The estimated cost for this system is approximately $360,000 capital cost and $6,500 annually based on the following assumptions:

- Cleaning is to be done four times per year.
- Water for flushing is free.,

4.4 Alternative Evaluation

Table 6 summarizes the costs for each of the alternative cleaning methods described in this section.

Table 6
Cleaning Method Alternative Cost Comparison

Tunnel Cleaning Alternatives	Capital Cost	Annual O & M Cost
Manual Cleaning	.$20,000	$101,000 per cleaning
Mechanical Cleaning air jets water nozzles	 $2.1 million $1.1 million	 $26,000 $7,500
Pulsed Flow using"Dam-Break" Wave Action	$0.95 million	$15,000
Pulsed Flow using CSO Pipeline Storage	$0.36 million	$6,500

5.0 Flushing Water Sources

The source of water for use in tunnel flushing is treated here as a separate question from the type of flushing used. It is likely that more than one source should be provided for flushing water, so that both wet weather 'and dry weather flushing could be accomplished.

There are five potential sources for flushing water. Possible sources for iterative flushing or ongoing flow include:

- Combined sewage.
- Reclaimed water.
- Groundwater.
- Water from Lake Union.
- City water mains. The cost estimates are provided to show cost of the acquisition of water for the flushing systems described in section 4. The capital and operations costs are for the water acquisition costs alone.

5.1 Combined Sewage

Combined sewage is recommended for the initial flush of the tunnel after a storm event. Combined sewage could also be used for iterative flushing, but would have some potential difficulties associated with its use. First for iterative flushes, use of upstream gates would be required to fill the pipes. Second, if the combined sewage were stored for a pulsed wave, the entire system would be subject to odor problems due to potential deposition from the flushing water. Third, there may not be enough flow to feed the system from this source during dry periods of the year, or that flow would have an unacceptably high concentration of solids.

If stored water is used for the initial tunnel flush, that flush does not have a cost associated with obtaining the water used. Additional flushes, such as would be required for tunnel options with lower slopes, will have a cost for the water used. Note that for all the cases, water from at least one alternate source should be available so that if odor complaints necessitate flushing during a dry period, water to perform that flushing is available.

5.2 Reclaimed Water

King County reclaims water at their East Division Reclamation Plant. This water could be trucked to onsite storage after storm events for use as flushing water. The estimated cost for this system is $41,000 annually, based on the following assumptions: Net cost of reclaimed water is equal to potable water. External tankage or piping could be used with minimal connection costs.

5.3 Groundwater

Groundwater could be extracted from the Lake Union area and pumped into the upper conduits. The disadvantages are (1), the need to obtain water rights from the State or the current water right owner and (2), the possible need for a pumping system. If there is any adjacent groundwater infiltration of significance entering the combined system, this would be an appropriate use for the infiltration. The advantage of this system is that the water would be "free", discounting the operational costs.

The estimated capital cost for this system is approximately $169,000, based on the following assumption:

- 3 wells and pumps at a depth of 100 feet adjacent to the CSO pipelines.

5.4 Lake Union

Water from Lake Union could be used to fill the CSO pipelines. This would require extensive permitting. Diversion of Lake Union water would require approval from the Army Corps of Engineers, Washington State Department of Ecology, and Washington State Department of Fisheries and Wildlife. Detailed research would need to be performed to identify regulatory fatal flaws prior to further consideration of this option.

The estimated cost for this system is approximately $214,000 capital and $19,000 annually based on the following assumption:

- A simple vertical turbine pump station with a capacity equal to 3 fire hydrants.

5.5 Potable Water

Potable water could be used to fill the CSO pipelines with flushing water. This would result in an ongoing cost for the potable water and would require a backflow preventor at each facility. A structure would be needed to hold reduced-pressure backflow prevention valves (double check valves). It could possibly be a small precast concrete vault placed above the ground surface. The primary advantage of this option is that a source of flushing water is available-year round.

The estimated cost for this system is approximately $60,000 capital cost and $42,000 annually based on the following assumptions:

- Three backflow preventers (one per pipe) of 1,500 gpm each (1 fire hydrant).
- Annual water cost of 4 washes at 430,000 gpm each.

Table 7 summarizes the capital and operations costs for the acquisition of water from the alternative sources.

Table 7
Flushing Water Alternative Costs

Water Source	Capital Cost	Annual Cost
Combined Sewage	0	0
Reclaimed Water	0	$41,000 per year
Groundwater	$169,000	$6,500 per year
Lake Union	$214,000	$19,000 per year
Potable Water	$60,000	$41,000 per year

6.0 Recommendations

The recommendations for tunnel cleaning are as follows:

- Steeper tunnel slopes increase the effectiveness of sediment transfer within the tunnel.
- A cunette is recommended to collect sediment and allow flushing of the sediments. Final sizing of the cunette is described in section 7.0.
- Steady state flushing is not feasible because of the large storage volume required to provide steady state flow.
- Pulsed flushing is recommended for tunnel cleaning.
- The recommended "pulsed" flushing method, if proved feasible, is to use the storage capacity of the South Lake Union CSO pipeline, Lake Union Tunnel CSO pipeline, and the Central Trunk CSO pipeline for storing "flushing" water. Control sluice gates would need to be installed in the East Portal/Drop Structure to create the "pulsed" flows.
- Iterative flushes may be required because it may take multiple "flushes" to remove sediment and reduce odors.
- The recommended flushing water source for iterative flushes is potable water or reclaimed water. While groundwater and Lake Union water are cheaper, the potential permitting issues make them less attractive. It is recommended that design provisions be provided in the CSO pipeline designs to allow connections to the City of Seattle water mains to provide flushing water supply. It is also recommended that connections for trucked reclaimed water also be provided.

Flow schematics for the proposed tunnel flushing process using the upstream CSO conveyance pipelines are attached as Step 1 through Step 7. They include:

Step 1: Tunnel Empty.
Step 2: Tunnel Filling.
Step 3: Tunnel Full, storm over.
Step 4: Tunnel Draining.
Step 5: Tunnel Empty with sediment.
Step 6: Tunnel Flushing.
Step 7: Refill for Iterative Flushing.

This option would allow more flexibility in the tunnel-flushing routine than would the patented "dam-break" gates and would provide more water to move the sediment. The gate operation could be programmed to give what experience indicates is the best flow sequence. Monitoring the sediment concentration, particle sizes, and related information at the pumping station as the tunnel is flushed at differing rates would allow optimization of flushing to minimize water use and maximize scouring. Another advantage is that these gates could be placed in a location more amenable to servicing.

The disadvantage of using the upstream pipes for storage instead of tanks within the tunnel is that the flow wave will be attenuated over the tunnel length. However, there is so much storage in the upstream pipes that a flow above the minimum required to move sediment could be sustained for at least a few minutes even at very high flow rates associated with maximized sediment transport.

There are many possible strategies for flushing the tunnel. A low rate of flow could be used to initially wet the tunnel followed by a sudden release of the remainder of the water. This wave would move at a faster velocity than the water released at the low rate. The wave would in essence "surf" on top of the water released initially and experience less drag at the wave front, thereby increasing the effective velocity. Pisano noted this effect in one of his papers.

The gates separating the upstream pipes from the tunnel would be closed prior to draining the tunnel. The trapped water could be used for an initial flush of the tunnel after the tunnel is drained. That water could be supplemented with water from other sources in the first flush and in subsequent flushes. The initial flush is "free" while additional flushes will cost more money because the water will have to be obtained from someplace to refill the upstream conduits. This means that the lower the slope and the more flushes required to clean the tunnel, the higher the cost to clean the tunnel. -

In order to maximize the available flow rates possible, the gates would be set with their bottoms below the invert of the supplying conduits. The portions of the available drop between the conduits and tunnel should be used to provide head to drive flow through the gates. This will allow a greater range of flows through the gates and allow pulses of flushing water to reach higher peak flows as desired to enhance the scouring effects of the flow.

Development of a final design for a flushing system utilizing existing pipe storage will require analysis of the effect of such storage on the upstream systems, analysis of gate and control locations, and integration of this system into the design of the East Portal/Drop Structure and other structures.

7.0 Cunette Sizing

Further design work was performed to optimize the final design of the cunette. The criteria used for sizing included a definition of minimum velocity of 2.5 to 3 feet per second, the design slope of 0.00129 feet per foot, a restriction on cunette width of 3 feet, and the assumption that the cunette design needed to work with either a one pass or two pass tunnel lining.

Alternative cunette sections reviewed for their hydraulic performance included circular, rectangular, rectangular with beveled bottom edges and triangular. The analysis also looked at 2 foot and 3 foot widths for each section and determined the flow required to achieve scouring velocities. The results indicated that the triangular section should be rejected out of hand. The rectangular sections achieve a higher velocity at a lower depth that the circular sections, but require more flow to get the velocity. The bevels in the rectangular sections retard the velocity at low depths, but then increase velocity and higher depths. The beveled sections rank between the rectangular and circular sections for velocity per amount of flow.

The amount of flow required to achieve 2.5feet per second (fps) velocity varied from 2.6 to 3.4 cfs. The amount of flow required to achieve 3 fps velocity varied from 5.2 to 6.5 cfs. Based on this information, a half round section of 2.5 feet diameter (30 inches) was determined to be a reasonable section hydraulically. This section would be easy to form, using a pipe section, and would achieve 2.99 fps velocity when full.

Further analysis was performed to determine appropriate slopes for the benches on either side of the cunette. As the flow increases and rises out of the cunette, the velocity decreases. The minimum velocity is dependent on the side slopes of the bench. Side slopes from 2% to 25% were reviewed. The following table shows the minimum velocity and the depth at which that minimum velocity occurs.

Table 8
Depth of Minimum Velocity

Slope (%)	Minimum Velocity (fps)	Depth of Minimum Velocity
25	2.77	1.5
20	2.66	1.5
15	2.5	1.55
10	2.27	1.55
5	1.96	1.4
2	1.85	1.35

Less cross slope leads to a lower minimum velocity. The impact of this lower minimum velocity is to reduce the effectiveness of the tunnel in moving sediment. Sediment will tend to not be transported as well on the shelf. Sediment accumulations on the shelf will be harder to clean off. The ideal shelf slope depends on the relative importance of several factors. If moving sediment is the primary factor, the steeper the

Slope the better. If access and mobility is the primary factor, then a much lower slope would be preferred. All of the shelf options evaluated required 13 to 15 MGD (20 to 23 cfs) to obtain 3 fps over the shelf. The 30% documents show a side slope of 10% for the bench above the cunette.

8.0 References

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2 Sediment Transport Technology: Water and Sediment Dynamics, Daryl B. Simons, Fuat Senturk, Water Resources Publications, 1992

9.0 Other Publications of Interest

Various papers by William C. Pisano and others.

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Open Channel Hydraulics, Ven Te Chow, McGraw Hill

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